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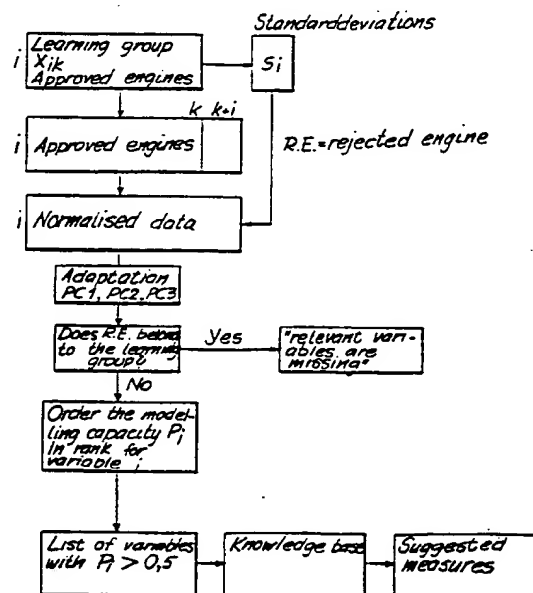
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(57) Abstract

Method of monitoring and/or diagnosing the operational state of a complicated, dynamic system constituted by a machine or an industrial process installation, a plurality (M) of state variables being measured at a plurality (N) of instants for the assembly of a corresponding measurement data (X_{ik}), which are processed statistically to form at least one reference class corresponding to a specific operational state. There is used here a group of measurement data (X_{ik}) serving as a learning group, which is adapted by linear projection to a new coordinate system with fewer coordinate axes. In a corresponding way, current measurement or calculation data are adapted to the new coordinate system, whereupon the distance between the current measurement or calculation data, on the one hand, and the measurement data corresponding to the learning group, on the other hand, is determined. If this distance exceeds a predetermined value, it is established which state variables that cause the deviation, by calculating the effect of the respective state variable on the variance along the respective coordinate axis in the new coordinate system.



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A METHOD FOR MONITORING THE OPERATIONAL STATE OF A SYSTEM.

The invention relates to a method of monitoring and/or
diagnosing the current operational state of a complicated
dynamic system constituted by a machine, apparatus or an
industrial process installation, in accordance with the pre-
amble to claim 1.

Such a method, intended for monitoring machine vibrations while
utilizing frequency analysis as well as sampling and pattern
recognition techniques is known from EP-A-84902732.1, the
reference class being frequency spectra and the pattern recog-
nition and detection means being adapted such as to calculate
the probability for each new frequency spectrum that it belongs
to a class other than the reference class. An abnormal opera-
tional state of the machine is determined when this probability
exceeds a predetermined limit.

According to the present invention, it is not only a question of
analysing occurring vibrations, but a large number of measurable
or calculable physical and possibly even logical parameters or
state variables, which to a greater or less extent may be con-
sidered as effecting the operational state of a complicated
system.

For example, in the operation and maintenance of complicated
machines, e.g. jet engines, measurements of a large number of
statistic and dynamic state variables are collected.
Accordingly, being able to readily indicate an unfavourable
combination of such variables is of the greatest importance
here, not only with regard to limit values decided for each
individual variable. The situation is similar for process
installations, e.g. paper manufacture or energy conversion
(such as in nuclear power stations).

There is further a desire of being able to calculate beforehand whether a proposed modification of a proven system will give acceptable results.

5 A paramount object of the present invention is thus to monitor and/or diagnose, possibly by calculation performed beforehand, and with the aid of mathematical, statistical methods, the existing operational state of a complicated machine, apparatus or process installation and in such a case either identify a
10 specific operational state (corresponding to a reference class) or determine a deviating operational state by simultaneously identifying what state variables cause the deviation.

This object is achieved by the process of steps disclosed in the
15 characterizing part of claim 1.

Statistic methods known per se are thus applied in accordance with the invention, these methods being used within so-called multivariate analysis, e.g. for rapidly discovering an undesired
20 state in a machine and pointing out individual variables or groups of variables responsible for this state. The method may be applied either in real time, namely to incoming measurement values, or to data bases, where the measurement values have been stored.

25 The invention will now be explained in more detail below and with reference to the accompanying drawings, where

Fig. A is a schematic diagram over the measuring and data equip-
30 ment, its structure being known per se, which is used in the method according to the invention;

Figs. 1 - 3 are flow diagrams corresponding to some application examples A, B and C;
35

Fig. 1a schematically illustrates a variant of the application example A; and

Fig. 3a is a variant of the flow diagram in Fig. 3.

5

The invention is founded on the following procedures:

10

The measurement values for different state variables V_i are obtained from suitable measuring sensors after amplification, filtering and digitizing (see Fig. A). For rotating machines both static and dynamic state variables may be used, e.g. the dimensions, taken from a coordinate table, of the machine components, clearance and play between given parts, throw and imbalance measured in a balancing machine, as well as different types of vibrations.

15

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Measurement of M different state variables V_i is repeated at different instances N times. The results (X_{ik} , $i = 1, \dots, M$; $k = 1, \dots, N$), which form a matrix or table with the dimensions $M \times N$ can be presented in a N -dimensional space as a cluster of N dots. The appearance of the cluster can be described, for example with the aid of a covariance matrix. If the dots have been collected during two different states of the system they will form, with the greatest probability, two clusters in the M space, provided that among the state variables there are precisely those which differentiate the current states in the system. A possibility is that the major part of the measurement data, which are derived from one or more known states of the system (so-called learning groups), are combined with a plurality of current measurement data which are to be tested (a test group).

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For easy handling of this type of multivariate measurement data it is proposed in accordance with the invention that a coordinate transformation is made. For such a transformation to be utilizable it must:

- reduce the number of coordinate directions;
- maintain the variance of the dot clusters; and
- separate different dot clusters in the best way.

5 A transformation found to meet these conditions is the so-called principal component method, which has been previously used in chemical data processing and in qualitative analysis of food-stuff. In this connection reference is made to the article
10 "Pattern Recognition: Finding and using regularities in multivariate data" by S. Wold, C. Albano, W.J. Dunn, K. Esbensen, S. Hellberg, E. Johansson and M. Sjöström in the publication "Food Research and Data Analysis" Applied Science Publishers, London and New York, 1983.

15 Applied to monitoring the state of machines, apparatus or industrial process installations, this principal component method means that multivariate measurement data X_{ik} are approximated by linear projection to a new coordinate system with fewer coordinate axes (L ; $L < M$) according to the
20 relationship:

$$X_{ik} = A_i + \sum_{a=1}^L B_{ia}T_{ak} + R_{ik}$$

25 where the new variables A , B and T describe the systematic part of the measurement data X_{ik} , and where the residue matrix R_{ik} describes the random part of X_{ik} . It should be pointed out that the transformation separates measurement data into parameters
30 (A , B) describing the state variables, on the one hand, and parameters (T) describing the system state at the respective measurement (k), on the other hand. The parameters T_{ak} describe the location of the k -state in the M -dimensional dot cluster and are therefore used for discriminating state classes.

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Adaptation of the principal components takes place in consecutive steps, one component at a time.

The procedure starts by normalizing the measurement data matrix X_{ik} with the standard deviation s_i of the respective state variable V_i , so that all variables will be of approximately the same order of magnitude, the mean value A_i being subtracted, i.e. the matrix $X_{ik} - A_i$ is formed. At this stage the first principal component

$$PC1 = B_{i1} T_{ik}$$

is adapted while using the so-called NIPAL's algorithm (Appendix A in the above mentioned article by Word et al), which in short means that beginning with an attempt or qualified guess with respect to the vector B, the vector T is calculated and the convergence is checked, which is repeated until the desired accuracy has been achieved. The first residue matrix $R_{ik1} = X_{ik} - A_i - PC1$ is then formed, which is used as the input matrix for determining the next (second) principal component, etc.

The number of components (L) is determined by the character of the data matrix. The process of adaptation can be terminated when no systematic parts remain in the residue matrix R_{ik} . For practical reasons the process can also be terminated after PC2. The state can then be depicted on a plane with coordinate axes corresponding to PC1 and PC2. A three-dimensional depiction can be constructed if the adaption is terminated after PC3. Three-dimensional depiction of measurement data are generally preferred.

It is of the greatest interest to find out how much different state variables contribute to the variance along each principal coordinate. In order to separate different state classes it is required, as mentioned above, that measurement data really do contain the state variables which are relevant for describing the classes. To decide this, the so-called modelling capacity P_{ia} of the state variable V_i along the respective coordinate axis a (a = 1, 2, ..., L) is defined:

$$P_{ia} = 1 - s_{ia}(R_{ika}) / s_i (X_{ik} - A_i)$$

where s_{ia} is the standard deviation for the residue matrix R_{ika} and s_i is the standard deviation for the matrix $(X_{ik} - A_i)$. P_{ia} varies between 0 and 1. If P_{ia} is close to 0, the variable V_i does not affect the variance along the principal coordinate in question, and in principle can be ignored. The modelling capacity can also be expressed as a percentage. In addition, the total modelling capacity P_{it} for PC1, PC2 and PC3 is defined according to the following:

$$P_{it} = \sqrt{(P_{i1}^2 + P_{i2}^2 + P_{i3}^2)/3}$$

Variables with a total modelling capacity P_{it} close to 1 are denoted "strong" variables. Strong variables are relevant for identifying different states, particularly fault states. Knowledge of these variables helps the operator to identify faults in machines, for example, or may be used in coaction with a knowledge base for automatic fault identification.

Some practical examples A, B and C of the method in accordance with the invention are given below.

Example A. Analysis of a data base with motor parameters

(see Fig.1)

In connection with the inspection of a jet engine, about a hundred different static and dynamic variables in the engine are measured. Thus, e.g. tolerance and throw in different parts of the rotor-stator system are measured accurately. The measurements are placed in a data base. When an engine has been approved after inspection, these measurement values are stored together with the engine documents. On the other hand, when an engine has been rejected, attempts have been made in different

ways to search among about a hundred measurement variables for the one or ones which have caused the rejection. This is an insolvable problem using elementary statistics as the sole aid. The use of conventional packages for advanced statistic analysis is unfortunately too time-consuming for enabling their operational use.

However, in applying the inventive method, about ten data base posts from approved engines are used as a learning group. The post for the tested, rejected engine is added to the table (matrix). After principal coordinate transforming, the variables are ordered in rank with a modelling capacity according to size. In this way the one or ones of the state variables which are responsible with the greatest probability for rejection of the motor can be indicated. In combination with a knowledge base (a rule system) directions as to required technical measures can be worked out. If the method is applied before the final check in a test bench economies can be made in many cases, since the number of rejections after checking can be reduced.

A variation of this example is that the data vectors (the columns in the total data matrix) for the approved engines are divided into sections corresponding to different work stages j (see Fig. 1a) during assembly of the engine ($j = 1, \dots, P$). In a corresponding way the data vector is divided for the tested engine and the analysis is made of each terminated work stage of a growing data matrix. This gives the possibility of breaking off the costly assembly process as soon as it is found that the tested engine will belong to the group of non-approved engines. At this stage the problem can be solved by using another selection of parts or further adjustment.

Example B. Checking blade distribution in rotor discs

(see Fig. 2)

Hitherto, the blades in a rotor disc are distributed according to simple rules decided by the manufacturer, with respect to the momentum weight of each blade. Computer programs calculating the distribution of blades around the rotor disc have also begun to come into use. Such a program distributes the blades with reference to their momentum weights so that inbalance is minimized. The method in accordance with the present invention enables the checking of a blade distribution arranged according to experience or calculation by comparison with previous, successful blade distributions, preferably from the same engine. Information in a data base containing such distributions of momentum weights which have given satisfactory dynamic properties are compared with a proposed distribution. It is here possible to obtain a measure of the quality of goodness of the distribution (distance to the group "successful distributions"), and an account of the blades causing possible negative dynamic properties in the rotor stage (strong variables) can thus be obtained. It is also possible to test several proposed distributions simultaneously.

Example C. Monitoring and advising with the engine running on a test bench (see Fig. 3).

When running an engine on a test bench, a large number M (usually about a hundred) operational variables are measured and stored. In modern test bench equipments the positions of all manual controls handled by the operator are also read off. Hitherto, the automatic monitoring is arranged such that maximum and minimum limits are given for certain essential variables, and that the system gives an alarm for certain programmed combinations of discrete and logical variables. The system thus gives an alarm for previously known undesired situations.

The inventive method can here be applied according to two different variations for an engine running on a test bench:

Variation 1. A large learning group is formed containing
5 2 - 3 measurements for each permitted operational situation
(corresponding to a specific reference class). Each new measurement ("present state" in Fig. 3) is continuously added to the
table or data matrix thus obtained. The new measurement (a dot
10 in the M-dimensional space) is tested with respect to its
distance to the learning group. If the new dot is outside those
of the learning group, a deviating stage is established and
possible strong variables are accounted for. If measures taken
by the operator give rise to strong variables the system can,
with support of a knowledge base, give the operator advice and
15 information about suitable measures in this situation. Possible
operator errors can be discovered and dealt with in this way.

Variation 2. Several learning groups are formed, one for each
interesting operational situation. Each learning group contains
20 about ten measuring points coming from this situation. Certain
undesired situations, e.g. faults or errors, can be stored among
the learning groups. Each new measuring point, or several consecutive incoming measuring points can then be tested against
the learning groups. By searching for the best adaptation to a
25 learning group, the operational situation can be identified with
great certainty. A simultaneous account of strong variables can,
in combination with a knowledge base, be used for achieving a
diagnosis and for giving advice with respect to possible
measures.

30 Both variations can be used both in real time as well as
subsequently for analysis of collected measurement data. Both
variations can further be used on all types of machines,
apparatus or industrial process installations, where a large
35 number of operational variables make the situation difficult for
a human being to comprehend.

This method can be made even more effective (see Fig. 3a) if the data vector in question ("present state") is transferred to an autoassociative neural network, e.g. of the type ART (Adaptive Resonance Theory Network), as described in Carpenter, G.A., Grossberg, S., "A Massively Parallel Architecture for a Self-Organizing Neural Pattern Recognition Machine", Computer Vision, Graphics and Image Processing 37, pp 54-115, 1987. The network is trained with typical data from normal operational conditions. The remaining part of the data flow is only activated on the discovery of a new category, for then carrying out the complete statistical analysis. In this way the statistical analysis does not need to be made during normal operational conditions.

CLAIMS

1. Method of monitoring and/or diagnosing the current operational state of a complicated, dynamic system constituted by a machine with a plurality of components, an apparatus or an industrial process installation with a plurality of state variables specific to the process, such as temperatures, flows, etc, a plurality (M) of physical and possibly also logical state variables ($V_i, i = 1, 2, \dots, M$) for said system being measured at a number (N) of instances ($t_k, k=1, 2, \dots, N$) for making up a corresponding number (MxN) of measurement data ($X_{ik}; i = 1, 2, \dots, M; k = 1, 2, \dots, N$), which are processed according to statistical methods in a computer for forming a plurality of reference classes corresponding to specific operational states of the system, the current measurement or calculation data ($X_{ik}; i = 1, 2, \dots, M$) being compared with said reference class or classes for diagnosing the corresponding, current operational state of the system, characterized in that

- a group of measurement data ($X_{ik}; i = 1, 2, \dots, M; k = 1, 2, \dots, N'; N' < N$) derived from the measurement of said state variables serves as a learning group for forming the respective reference class, these measurement data (X_{ik}) being adapted in a manner known per se by linear projection to a new coordinate system with fewer coordinate axes ($L; L < M$) while retaining the variance of the measurement data and the selectivity of different operational states, according to the relationship

$$X_{ik} = A_i + \sum_{a=1}^L B_{ia} T_{ak} + R_{ik}; \quad i = 1, 2, \dots, M; k = 1, 2, \dots, N'$$

where A_i is the mean value of the respective state variable (V_i);

B_{ia} and T_{ak} are a reduced number of parameters in the new coordinate system essentially corresponding to the systematic part of the measurement data;

R_{ik} is a residue matrix essentially corresponding to the random part of the measurement data;

- said current measurement or calculation data (X_{ik} ; $i = 1, 2, \dots, M$; $N' < k < N$) are adapted in a corresponding manner to said new coordinate system,
- the current operational state of the system, possibly after checking in an autoassociative network as to whether the current operational state belongs to any reference class, is compared with said specific operational state by determining the mutual distance between said current measurement or calculation data, on the one hand, and the measurement data corresponding to the respective learning group, on the other hand, in the new coordinate system, and
- in the case where said possible check has not been carried out and said distance falls below a predetermined value, the corresponding specific operational state of the system is identified and, in the case where said distance exceeds a predetermined value, it is determined what state variables and, on the basis thereof, what component(s) or state variables(s) specific to an industrial process, respectively, that cause the deviation by calculating the effect of the respective state variable on the variance along the respective coordinate axis in the new coordinate system.

2. Method as claimed in claim 1, characterized in that said adaptation of measurement data (X_{ik}) to the new coordinate system is carried out in steps, the respective coordinate axis in the each step (a ; $a = 1, 2, \dots, L$) being selected such that the variance for said parameters (B_{ia}, T_{ak}) along this coordinate axis is minimized.

3. Method as claimed in claim 2, characterized in that said stepwise adaptation is carried out according to NIPAL's algorithm.

4. Method as claimed in claim 2 or 3, characterized in that the new coordinate system has one, two or three coordinate axes ($L=1,2$ or 3).

5. Method as claimed in any one of claims 2 - 4, characterized in that said calculation of the effect on the variance along the respective coordinate axis caused by the respective state variable is carried out on the basis of the so-called modelling capacity (P_{ia} ; $a = 1, \dots, L$) of the respective state variable according to the formula:

$$P_{ia} = 1 - s_{ia}(R_{ika})/s_i(X_{ik} - A_i);$$

where s_{ia} and s_i are the standard deviations of R_{ika} and A_i , respectively; and

R_{ika} is the residue matrix after the respective adaptation step (a);

this modelling capacity (P_{ia}) being able to assume values between 0 and 1 and the total modelling capacity (P_{it}) of the state variable being calculated as a combination of the values of the different adaptation steps (a) so that a total modelling capacity between 0.5 and 1 points out the state variable in question as contributing to said deviation.

6. Method as claimed in claim 5, characterized in that the total modelling capacity (P_{it}) of the respective state variable is calculated according to the formula:

$$P_{it} = \sqrt{\frac{P_{i1}^2 + \dots + P_{iL}^2}{L}}$$

7. Method as claimed in any one of the preceding claims, characterized in that said measurement or calculation data (X_{ik}) are normalized with the standard deviation (s_i) of the respective state variable, calculated on said learning group, before said adaptation to the new coordinate system.

8. Method as claimed in any one of the preceding claims for analysing previously made measurement data stored in a data base and relating to several systems of the same type, said systems having been approved of or rejected on inspection or test operation, c h a r a c t e r i z e d in that a plurality of measurement data posts derived from approved systems are used as a learning group, and one or more measurement data posts derived from rejected systems are used as said current measurement data, there being produced a list of the state variables which have, with a certain probability, contributed to rejection of the system.

9. Method as claimed in any one of claims 1 - 8 for monitoring different operational states in test running of complicated systems, which are at least partially controlled manually by an operator, c h a r a c t e r i z e d in that a plurality of measurement data posts derived from permitted operational states are used as one or more learning groups, which are successively supplemented with current measurement data derived from the test run, deviating operational states and state variables causing these being accounted for continuously for diagnosis and possible measures to be taken by the operator.

10. Method as claimed in any one of claims 1 - 7 for calculating beforehand whether a proposed modification to a tested system will give acceptable results, c h a r a c t e r i z e d in that measurement data posts, derived from a plurality of tested and approved systems of a similar kind, are used as a learning group, whereas computer calculated data corresponding to said proposed modification are used as said current data.

Fig. A

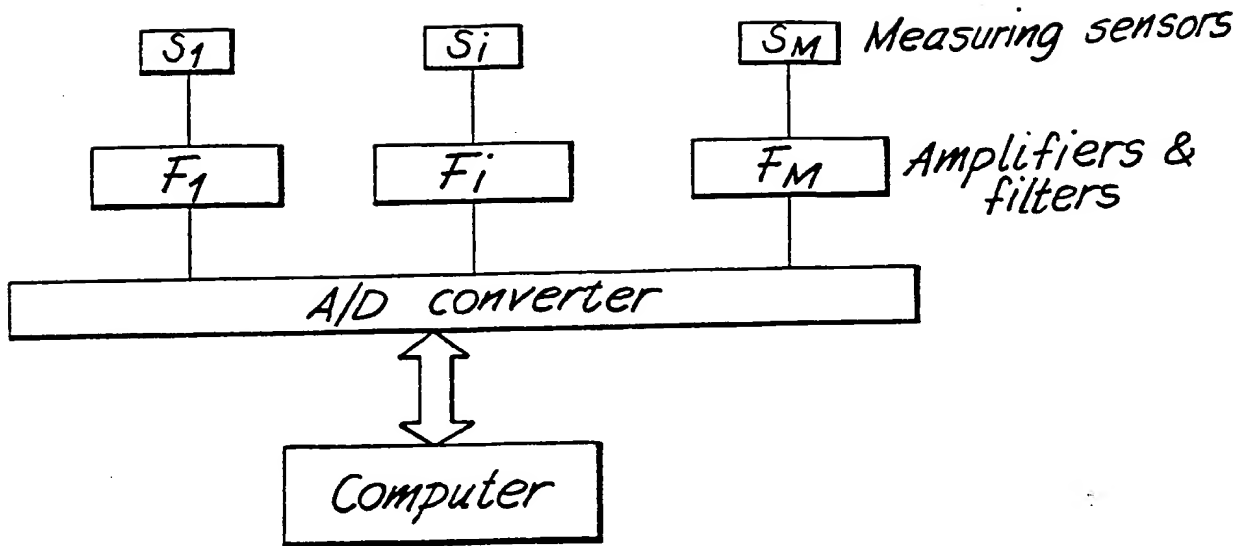


Fig. 1a

	k	$k+i$
Stage i		
Stage j		
Stage p		
Approved engines	Tested engine	

Fig. 1

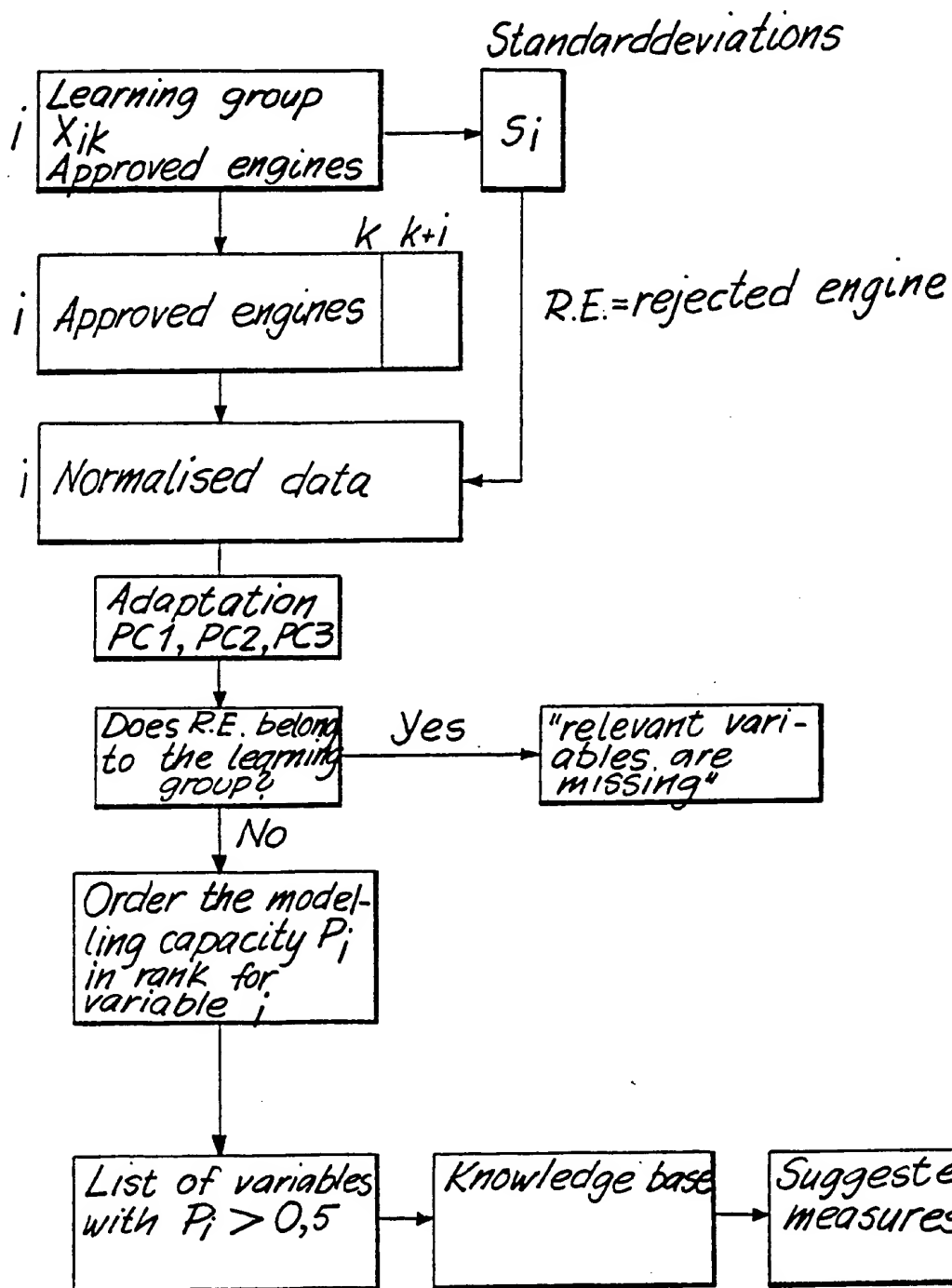


Fig. 2

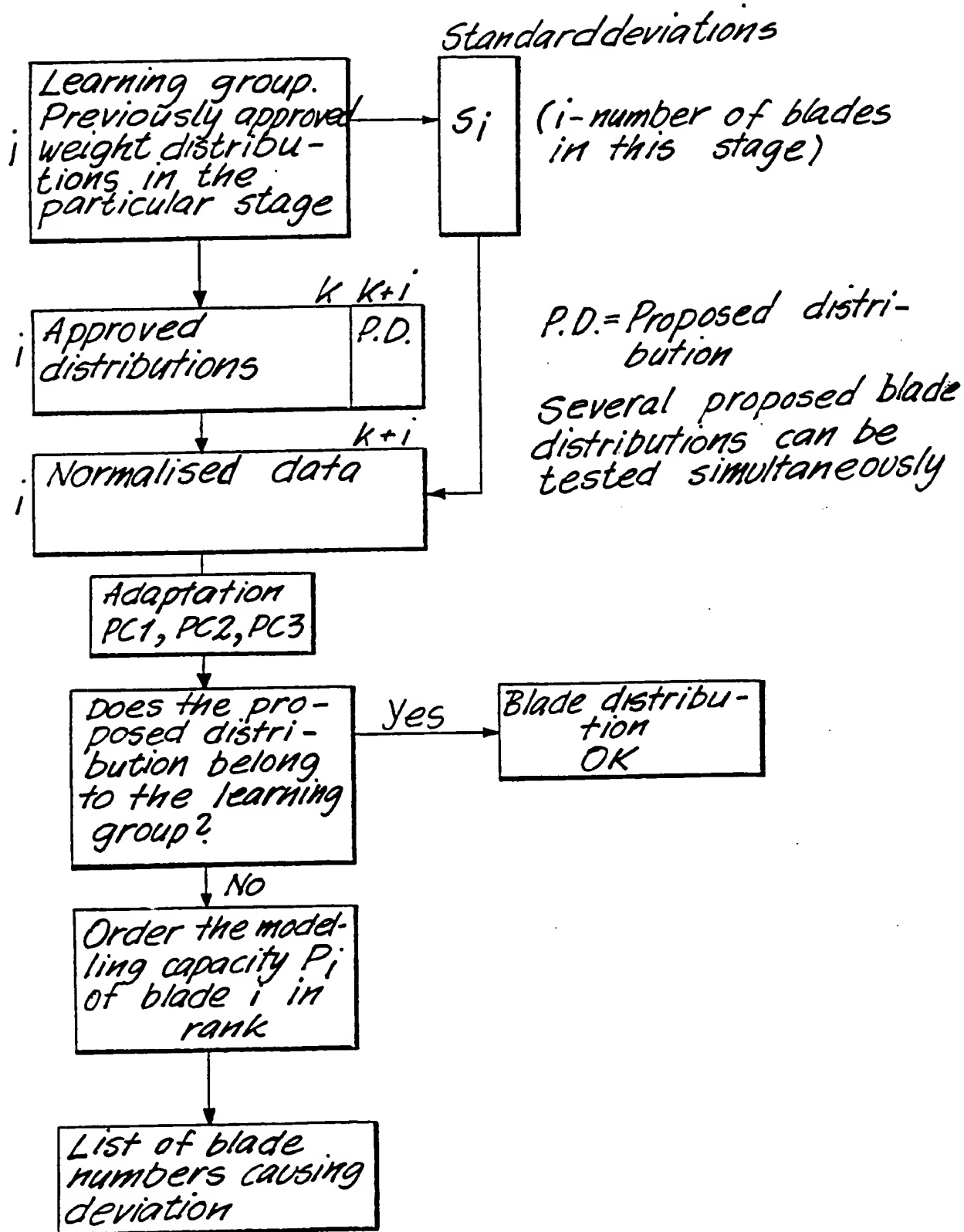


Fig. 3

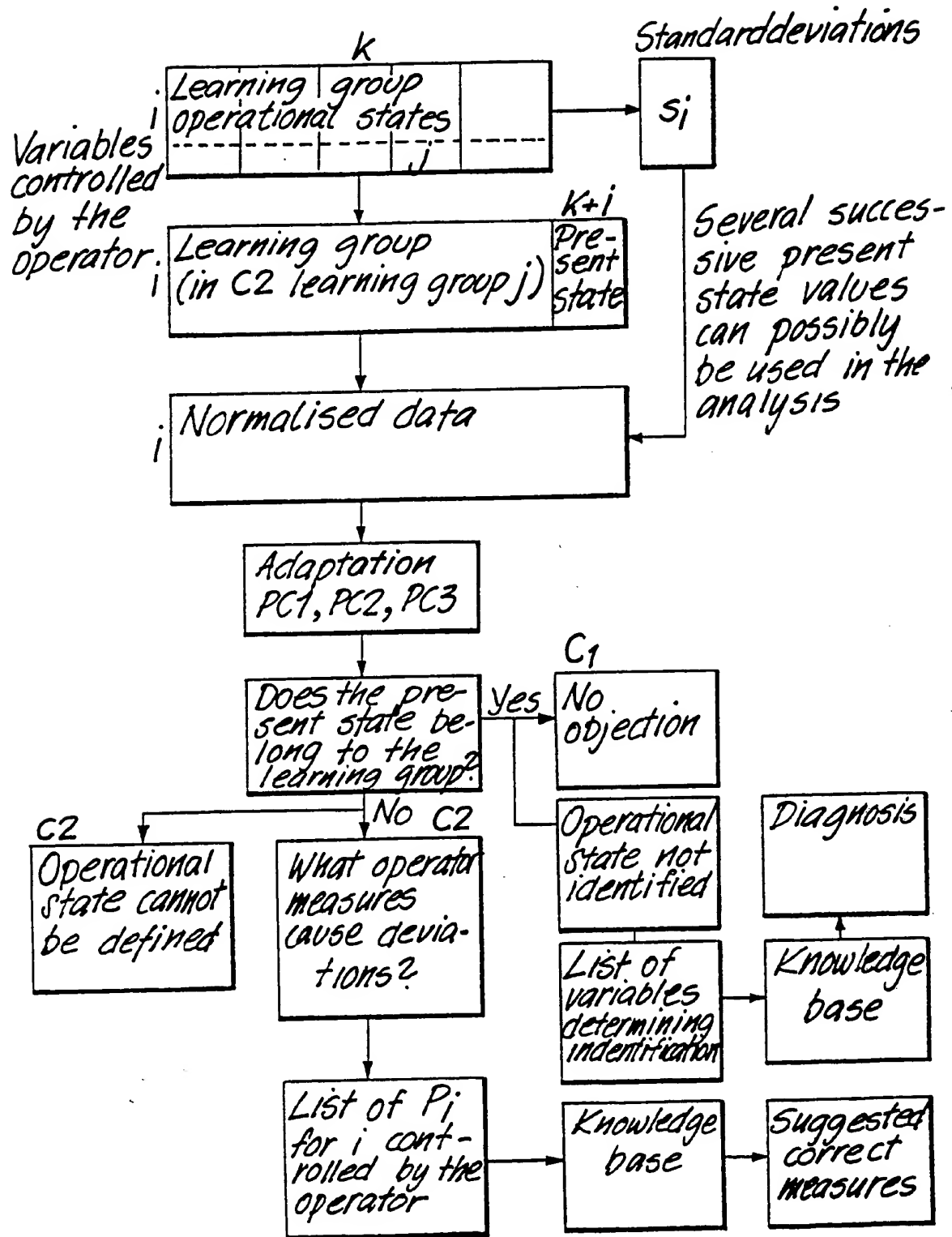
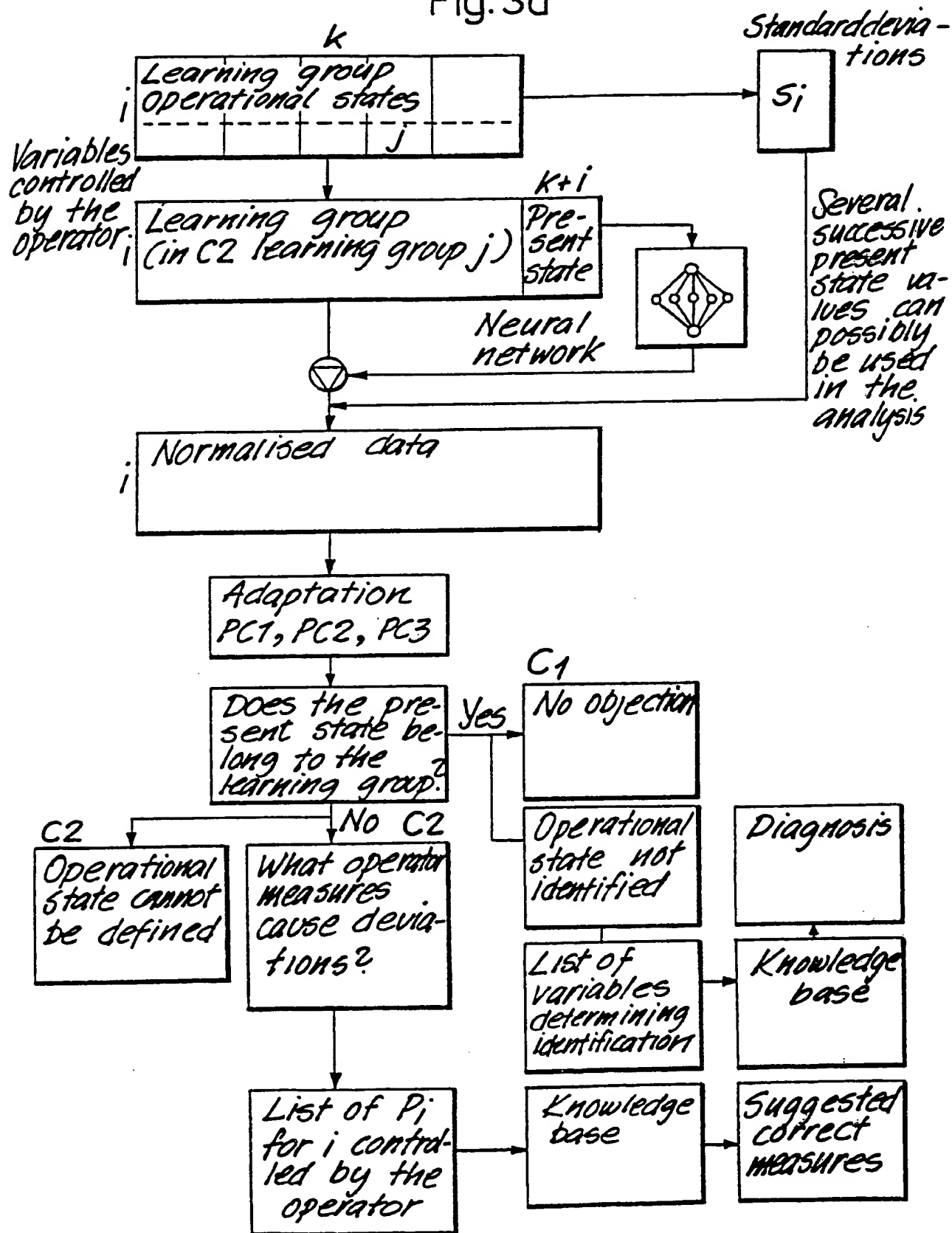


Fig. 3a



INTERNATIONAL SEARCH REPORT

International Application No PCT/SE 90/00414

I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) ⁶ According to International Patent Classification (IPC) or to both National Classification and IPC IPC5: G 07 C 3/00								
II. FIELDS SEARCHED <div style="text-align: center;">Minimum Documentation Searched⁷</div> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 20%;">Classification System</th> <th style="width: 80%;">Classification Symbols</th> </tr> <tr> <td style="height: 40px; vertical-align: bottom;">IPC5</td> <td style="vertical-align: bottom;">G 07 C</td> </tr> </table> <div style="text-align: center; font-size: small;">Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in Fields Searched⁸</div>			Classification System	Classification Symbols	IPC5	G 07 C		
Classification System	Classification Symbols							
IPC5	G 07 C							
SE,DK,FI,NO classes as above								
III. DOCUMENTS CONSIDERED TO BE RELEVANT⁹ <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 10%;">Category *</th> <th style="width: 60%;">Citation of Document,¹¹ with indication, where appropriate, of the relevant passages¹²</th> <th style="width: 30%;">Relevant to Claim No.¹³</th> </tr> <tr> <td style="vertical-align: top;">A</td> <td style="vertical-align: top;"> Food Research and Data Analysis, issued 1983 (Applied Science Publishers, London and New York) S. Wold et al, "Pattern Recognition: Finding and using regularities in multivariate data", pages 146-189 Mentioned in the description <div style="text-align: center;">-- -----</div> </td> <td style="vertical-align: top; text-align: center;">1</td> </tr> </table>			Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³	A	Food Research and Data Analysis, issued 1983 (Applied Science Publishers, London and New York) S. Wold et al, "Pattern Recognition: Finding and using regularities in multivariate data", pages 146-189 Mentioned in the description <div style="text-align: center;">-- -----</div>	1
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<div style="display: flex; justify-content: space-between; font-size: x-small;"> <div> <p>* Special categories of cited documents:¹⁰</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p> </div> </div>								
IV. CERTIFICATION <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; padding: 5px;"> Date of the Actual Completion of the International Search 31st August 1990 </td> <td style="width: 50%; padding: 5px;"> Date of Mailing of this International Search Report 1990 -09- 1 1 </td> </tr> <tr> <td style="width: 50%; padding: 5px;"> International Searching Authority <div style="text-align: center;">SWEDISH PATENT OFFICE</div> </td> <td style="width: 50%; padding: 5px;"> Signature of Authorized Officer Bertil Nordenberg <i>Bertil Nordenberg</i> </td> </tr> </table>			Date of the Actual Completion of the International Search 31st August 1990	Date of Mailing of this International Search Report 1990 -09- 1 1	International Searching Authority <div style="text-align: center;">SWEDISH PATENT OFFICE</div>	Signature of Authorized Officer Bertil Nordenberg <i>Bertil Nordenberg</i>		
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International Searching Authority <div style="text-align: center;">SWEDISH PATENT OFFICE</div>	Signature of Authorized Officer Bertil Nordenberg <i>Bertil Nordenberg</i>							

**ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.PCT/SE 90/00414**

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the Swedish Patent Office EDP file on **90-08-02**
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date

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